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PROCESS DEVELOPMENT FOR CLADDING APT TUNGSTEN TARGETS

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ABSTRACT

This report describes development of processes for cladding APT Target tungsten components with a thin layer (0.127-mm) of Alloy 718, Alloy 600 or 316L stainless steel alloy. The application requires that the cladding be thermally bonded to the tungsten in order to transfer heat generated in the tungsten volume to a surrounding coolant. High temperature diffusion bonding using the hot isostatic processing (HIP) technique was selected as the method for creating a metallurgical bond between pure tungsten tubes and rods and the cladding materials. Bonding studies using a uniaxially loaded vacuum hot press were conducted in preliminary experiments to determine acceptable time-temperature conditions for diffusion bonding. The results were successfully applied in cladding tungsten rods and tubes with these alloys. Temperatures 800°-810°C were suitable for cladding tungsten with Alloy 600 and 316L stainless steel alloy, whereas tungsten was clad with Alloy 718 at 1020°C.

I. INTRODUCTION

The need for cladding APT tungsten target materials was recognized when corrosion of water-cooled unclad tungsten rods was observed during a proton irradiation experiment at LANCE. Activated tungsten compounds were released into the coolant stream and significant corrosion of the tungsten rods (an implied steady state corrosion rate of >1mm/yr) occurred at the location of proton beam impact.[1] The APT tungsten target is configured as a series of 12 ladders with from 16 to 28 rungs per ladder. Each rung contains a series of four to six concentric tungsten tubes and has a central clad rod. All of the tungsten rods and tubes are 35-cm long. A 1.106-mm spacing between clad tubes, and between clad tubes and the central rod provides a water-cooling gap for internal and external surfaces of the clad tubes, and the external surface of the clad rods. Tungsten wall thickness varies from 2.16-mm to 11.2-mm. The internal and external surfaces of each tube are clad with a 0.127-mm thick layer of a corrosion resistant material. The ends of the rings are also clad with thicker layers of the same materials. Alloy 718 alloy was selected as the primary cladding material because of its high strength and superior corrosion resistance. In addition, there is an existing experience base of successful application of this alloy for water cooled proton beam windows at LANCE. Alloy 718 also has a superior oxidation resistance. Stainless steel alloy 316L was selected as a backup cladding because an extensive irradiation database is available for this material, and because its lower yield strength, and potentially lower bonding temperatures, would more readily accommodate thermal expansion differentials between the alloy and tungsten during a bonding temperature cycle. Alloy 600 was selected as a second backup for the latter reason, and because it has oxidation resistance superior to 316L stainless steel (SS). Figure 1 illustrates the clad tube and rung designs. The cladding process selected must create intimate contact and an excellent thermal bond between the cladding, end cap and tungsten to uniformly transfer heat generated in the tungsten volume by proton bombardment to the water-cooled clad tungsten surfaces. Bonding of the tungsten to the end cap is also important for support of the assemblies between end plates. The design also requires that the cladding be bonded to the outside and inside diameters of end caps for clad tubes, and to the outside diameter of end caps of clad rods to allow accurate end cap finish machining. Metallurgical bonding accomplished by inter-diffusion of the tungsten and cladding components would provide such bonds if diffusion were limited so that no new phases with objectionable properties were formed at the interface. The following sections describe the selection of the bonding method, experiments to establish bonding conditions, and successful cladding of tungsten tubes and rods with Alloy 718, and tubes with the three alloys of interest. A final section discusses suggestions and recommendations for further work and testing.

II. Technical Approach

Several processes were considered for accomplishing the required thermal bond between tungsten and the cladding. Solid state diffusion bonding using hot isostatic processing (HIP) was selected for study as the best available option for providing stable heat transfer conditions. HIP would apply sufficient inert gas pressure to maintain contact between the cladding and tungsten ring interfaces throughout the bond cycle, and cause the cladding to creep into intimate contact with the tungsten at temperature to allow a uniform diffusion bond to occur. Because a HIP cycle of the type contemplated takes about eight hours to perform, and requires an encapsulated sample design, it was decided to perform initial bonding studies using a diffusion pumped, liquid nitrogen trapped uniaxial vacuum hot press. The press is capable of operating at pressures of $<2X10^{-6}$ to heat and apply a load between 35 and 70Mpa to 18.26-mm diameter disk sample stacks. These conditions would cause the sample interfacing surfaces to creep into intimate contact. The sample stack arrangement planned would expose tungsten-to-cladding alloy and cladding alloy-to-cladding alloy interfaces to the same bonding conditions. Once a set of bonding conditions were defined as acceptable through metallographic examination of the bonded interfaces for a cladding selection, bonds of clad tungsten tubes and rods would be accomplished and evaluated for bond quality using both non-destructive and destructive techniques. The results of these experiments, and tests to evaluate bond strength and stability, would allow preparation of a specification for manufacture and inspection of clad tungsten components for APT target application.

III. Uniaxial Bonding Experiments

A. Initial Selection of Bonding Parameters

A primary objective of these experiments was to create diffusion bonds without second phase layers anticipated to be brittle (for example, WFe_2, W_2Fe_3, and WNi_4) at the tungsten-alloy interface. Also, proton-neutron irradiation testing at APT prototypic conditions of machinable tungsten alloys prepared by liquid phase sintering of compositions containing 97wt-% tungsten with 3wt-% copper-nickel-iron showed behavior that is thought unacceptable (the samples crumbled during hot cell handling).[2] The poor irradiation response of such alloys, typically sintered in the range 1425°C to 1650°C, provides an argument for bonding at temperatures far below those where a liquid phase would be expected to appear at the tungsten-cladding interface.

1. Tungsten-Alloy 718. Bonding parameter selection was guided by Alloy 718 properties and anticipated response to various thermal cycles that might be used for bonding. There was concern that if the alloy were in fully aged condition during cooling from the bonding cycle, the stronger material would have a greater tendency to rupture the bond in accommodating the thermal expansion difference between the alloy and tungsten. This was viewed as a particular problem between the internal diameter of the tungsten tube and the internal cladding layer. It was decided that the bonding conditions for Alloy 718 should be selected from within the solution annealing temperature range of 926°C to 1065°C and that a constant time at temperature of one hour would be used for all bonding experiments. The target assemblies would thus be exposed only to temperatures above those where precipitation hardening would cause the material to strengthen during the bonding step. Bonding in the upper portion of the annealing range was also thought to carry the advantage of bonding under conditions where the alloy would have the greatest tendency to creep into intimate contact with the tungsten structure. Cooling through the temperature range where aging would start should be accomplished as quickly as possible to preserve material ductility and low strength. Even though there are significant microstructural differences when compared to a drawn tube, data for ~16-mm diameter hot-rolled Alloy 718 bar annealed at 1065°C, serves to illustrate this approach. The yield strength (0.2% Offset) after annealing is 334.4MPa, after aging, 1,082.5Mpa[3], over a factor of three increase in strength for the aged product. Initial bonding trial temperatures of 1038°C and 1065°C were selected to bond this alloy.

2. Tungsten-Alloy 600 and 316L SS. The second series of bonding tests to tungsten included samples of Alloy 600 and 316L SS. Samples of Alloy 718 were included in these tests to serve as a basis for comparison to earlier tests. The first bonding tests for Alloy 600 were performed within the temperature range selected for Alloy 718 given that both are high nickel alloys. For 316L SS, bonding in the temperature range 800°C to 950°C was investigated.

B. Sample Preparation /Sample Stack Geometry

Machined samples were chemically cleaned for bonding by ultrasonic degreasing in analytical reagent grade acetone, chemical etching in appropriate acid mixtures followed by rinsing in distilled water and drying with acetone or ethyl alcohol. A slight discoloration on the surface of Alloy 718 disks was polished from the surface using lubricated 600-mesh silicon carbide paper before the initial solvent cleaning. After cleaning, all samples were kept packaged until use, and handled with clean lint free gloves for bonding studies to prevent contamination. Figure 2 shows how samples were stacked for bonding in the hot press in an arrangement used initially for bonding a single sample set of Alloy 718 to itself, and to tungsten, although sample stacks representing all three alloys of interest were later assembled for bonding tests at one temperature. Thin tantalum layers were positioned at each end of the sample stack to prevent diffusion of carbon from the graphite plungers into the components being bonded. Alloy layers, 1.016-mm thick, are shown in the figure, however, each alloy composition used was purchased in a different thickness for these studies in order to help maintain identity. Tungsten disks 0.127-mm thick were used for all of the bonding runs. The diameter of all bonding stack components was 18.29-mm. Measurement of bonding temperature was accomplished with a calibrated Micro Optical infrared pyrometer manufactured by the Pyrometer Instrument Company, Northvale, NJ. Emissivity corrections were made for the material being heated for each bonding run.

C. Uniaxial Bonding Results

The uniaxial bonding test experiments covered in this report are given in Table 1, below: Results for these experiments are described roughly in the sequence performed as indicated in Table 1.

Series	Temperature, °C	Sample Couple Compositions
1	1065	Alloy 718-W
1	1038	"
2	1020	"
2	990	"
3	1050	W-Alloy 600, W-Alloy 718
3	990	"
3	800	W-316LSS
3	950	"
3	1000	W-Alloy 600, W-Alloy 718
4	810	W-316LSS, W-Alloy 600

Table 1. Uniaxial Bonding Run Tests, Alloy-Tungsten

1. Alloy 718-Tungsten Bonded at 1065°C and 1038°C. Both tests performed at these temperatures at a load of 69Mpa, produced excellent mechanical bonds however both tungsten and Alloy 718 extruded radially at 1065°C, resulting in separations in the 0.125-mm thick tungsten disk near the periphery of the sample. The initial microstructure of the rolled tungsten sheet with elongated grains changed to an equiaxed structure during this heat treatment. Dark particles within the body of the alloy for both samples were examined with the scanning electron microscope (SEM) using energy dispersive x-ray analysis (EDAX) and were determined to be precipitated niobium carbide. Only limited deformation (<0.005-inches) was observed during the time the 1038°C sample was at temperature. Neither of the bond microstructures showed development of a resolvable interfacial phase at the juncture between the two layers when examined optically at 500X.

2. Alloy 718-Tungsten Bonded at 1020°C and 990°C. Optical microscopy examination of etched samples pressed at 990°C and 1020°C, Figure 3, revealed the presence of cracks in the interior of the W layer in both samples. The cracks lie in the plane parallel to the bonds and run from near the center of the sample to the edge of the sample (do not run to the bond interfaces). A second feature was the seeming integrity of the bond between the W and Alloy 718,as well as lack of evidence of formation of an interfacial phase. Scanning-electron microscopy (SEM) examination was carried out in the region surrounding the W-to-Inconel 718 bond. Evidence of a limited amount of diffusion of some of the elements in Inconel 718 into the W was seen. Extensive inter-granular cracking was seen in the interior of the W layer. An electron-microprobe analysis was performed to evaluate interdiffusion for the sample bonded at 1020°C. The microprobe traces were performed at three locations in the bond and typical results, presented in Figure 4, except that Al and Ti are not shown in the figure, may be summarized as follows:

- Appreciable (greater than 0.1wt.%) amounts of tungsten penetrated into the Alloy 718 to a distance of 5-6μ.
- Neither Al, Ti or Nb appeared to have penetrated into the tungsten from the Alloy 718.
- Small amounts (greater than 0.1wt.%) of Fe, Cr, and Ni penetrated about 3 to 6μ into the tungsten from the Alloy 718.

Both the optical and SEM metallography indicate two essential features about the quality of the tungsten-to-Alloy diffusion bond produced by bonding at 990°C and 1020°C. In each case, the quality of the bond is excellent. The elastic stress created in the tungsten on restrained cooling from the 1020°C bonding temperature to room temperature was calculated[4] at 2,638Mpa, (4-6 times that of the ultimate tensile strength of tungsten at 20°C). This stress level is high enough to cause intergranular cracking in the tungsten a distance away from the bond line and explains the defects observed.

3. Alloy 718 & Alloy 600-Tungsten Bonded at 1050°, 1000°, and 990°C. At each temperature, Alloy 718 appeared to be strongly bonded to tungsten without appearance of an interfacial phase when examined with the Scanning Electron Microscope (SEM)

at 2000X. Bonds at the interfaces between two layers of the same composition appeared to be excellent for both alloys. For tungsten-Alloy 600 samples the presence of a brittle interface layer (indicated by regions of fracture within the interface layers of bonded samples) of 1.49μ thickness at 1050°C and 0.86μ at 1000°C was observed. Analysis of this layer for the sample bonded at 1050°C showed the major constituents to be chromium at 6.08wt.%, iron at 1.85wt.%, nickel at 16.70wt.% and tungsten at 75.24wt.%. It was decided that a lower bonding temperature should be used for this material combination so that the brittle layer wouldn't form. In addition, interdiffusion should be limited to about 0.2μ so as to provide only the minimal amount required to establish a good metallic bond. Using the diffusion profile measured for nickel for the tungsten-Alloy 718 bond sample at 1020°C for this study, and data for diffusivity of nickel in pure tungsten[4], diffusion depths of nickel in tungsten were calculated for several temperatures for one hour bonding times. The calculations showed the desired bonding temperature for Alloy 600 to yield diffusion of nickel into tungsten to a depth of about 0.2μ was around 800°C. The results for bonding tests in this temperature range for Alloy 600 and 316L SS are given in the following sections.

4. Tungsten-to-316L SS Bonded at 950° and 800°C. Optical metallography of 316L stainless steel bonded to tungsten at 950°C for one hour showed separations at one side of the tungsten layer. All samples bonded at this temperature showed characteristic flaws initiating at the interface then proceeding into the center of the tungsten layers. Samples bonded at 800°C appeared well bonded with no separations at interfaces between tungsten and 316L SS-see Figure 5. SEM examination at 4000X of the tungsten-to-316L SS interface bonded at 800°C showed no interfacial phases. Bonds of 316L to itself at 800°C appeared to be excellent. It was decided that tungsten-316L SS interfaces might well be bonded at the same temperature that should be suitable for Alloy 600, 810°C.

5. Tungsten-to-316L SS and Alloy 600 Bonded at 810°C. SEM examination of samples of 316L stainless steel and Alloy 600 bonded to tungsten at 810°C at 4000X showed uniform bonds with no secondary phases or flaws appearing at the interface between the alloys and tungsten. Figure 6a and 6b illustrate the appearance of the 316LSS and Alloy 600-to-tungsten bonded couples.

D. Selection of HIP Bonding Parameters

The uniaxial diffusion bonding studies indicated that Alloy 718 could be diffusion bonded to tungsten at temperatures between 1020° and 990°C. Examination of samples also indicated that a satisfactory bond would result between two layers of the alloy at these temperatures although some evidence of the initial interface was resolvable in microstructures of these samples. However, the Alloy 718-to-Alloy 718 bond microstructures were free from porosity or inclusions at the bond interfaces. It was decided to adopt 1020°C for HIP bonding Alloy 718 cladding to tungsten rods and rings. For 316L SS and Alloy 600, it was decided to perform HIP bonding at a temperature of 810°C as it was possible to avoid a harmful interfacial phase at that temperature and alloy-to-alloy diffusion bonds were satisfactory at that temperature.

The differences in coefficients of thermal expansion between tungsten and the cladding alloys under consideration requires that the HIP processing thermal/pressure cycle be designed to prevent the cladding layer from lifting from the surface to which it is to be bonded. For example, if a 14-inch long target tube or rod were to be heated to bonding temperature prior to the application of pressure, gaps would appear between the end caps and the ends of the tungsten components due to the greater heated length of the cladding. Subsequent application of bonding gas pressure would drive the thin cladding into the gaps and perhaps cause failure. A temperature/pressure cycle was devised for HIP bonding that avoided such problems and is shown for Alloy 718 and Alloy 600/316L SS bonding in Figure 7. For both bonding cycles, the pressure increases to values that maintain contact between alloy and tungsten through yielding of the cladding in advance of the temperature rise.

IV. Hot Isostatic Processing of Clad Target Tungsten Rods and Tubes

Tungsten components were purchased from several vendors, rods from Schwarzkopf Technologies, Franklin, MA, tubes fabricated by chemical vapor deposition (CVD) from Ultramet, Pacoima, CA, and tubes fabricated from pressed and sintered tungsten from Sylhan, LLC, West Babylon, NY. Superior Tubes, Collegeville, PA, fabricated Alloy 718 tubing for cladding 3.2mm tungsten rod. Century Tubes Inc., San Diego, fabricated all other tubing for cladding tungsten tubes

A. HIP Preparation and Processing

Cladding components were prepared by machining to form an envelope with which to encapsulate the tungsten component. For a tungsten rod, these consisted of two end caps and a tube machined so as to provide a net fit of the end caps to the ends of the rod after the weld joint was accomplished by electron beam welding. For tungsten tubes, the same approach was taken with the addition of a tight fitting cladding tube slid into the inner diameter of the tungsten. A portion of an engineering drawing in Figure 8 illustrates the design of the configuration for HIP processing of clad tungsten tubes. The end cap design provides a thick section of material for concentric support of the tubes on their inside diameters by projections from the orifice plate to prevent fretting wear on the thin tube wall.. All components were cleaned thoroughly by solvent degreasing followed by acid etching and rinsing in distilled water to remove any trace of surface oxide or contamination. Electron beam welding of the cladding assemblies was accomplished using a 140kv beam at very low current to accomplish welds on the order of 0.25mm deep located in the cap regions to avoid damage to the tungsten components. The weld joint interfaces were held together tightly with fixtures to control the weld configuration and uniformity. The last (cladding volume sealing) weld of each assembly was made after pumping on the weld chamber for a minimum of two hours to allow the cladding volume to be fully exhausted through light scribe marks placed at the weld joint faying surfaces to allow egress of gases. Assemblies were helium mass spectrometer leak checked then packaged in pure alumina tubes for protection and HIPed according to the schedules given in Figure 6. Details of the fabrication procedure for these assemblies were documented in an APT Project document.[5]

B. Alloy 718 Clad Tungsten Rods and Tubes

Metallographic examination was performed of a HIP bonded wrought tungsten rod clad with Alloy 718. Figure 9 illustrates the Alloy-to-tungsten interface and shows that the cladding has bonded to the end cap of the assembly. The flow of cladding and end cap material into void in the assembly created by chamfers or radii on the tungsten rod and Alloy 718 end cap is apparent in the photomicrograph. Figure 10 shows a 50.8mm long, 16.3mm outside diameter, 2mm wall CVD tungsten tube clad with Alloy 718. Depressions at each end of the clad tungsten tube at the interfaces between the tungsten tube and end caps can be seen. Ultrasonic examination of this tube, using a through transmission technique, showed the interface between tungsten and cladding to be well bonded. Examination of the assembly by eddy current testing showed no internal tungsten flaws. The visual examination of the clad assembly showed a wrinkle in the cladding due to an initial slight gap between the tube and the inside diameter of the cladding. The clad tube was sectioned to evaluate the bond integrity. Because of residual tensile stress in the cladding, the act of sample cutting caused the cladding to pull away from the tungsten. Fortunately, the diffusion bond is stronger than the CVD tungsten and the cladding separated from the cladding in the tungsten. Figure 11 illustrates this feature. Examination of a section that included the wrinkle showed that structure to be fully consolidated by the HIP process and without defects. Wrought tungsten tubes of 15.2cm length and similar diameter and wall thickness were also successfully clad and inspected by ultrasonic and eddy current testing methods.

C. Alloy 600 and 316L Clad Tungsten Tubes

CVD tungsten tubes of 15.2cm length. 16.3mm outside diameter and 1.9mm wall were clad with these alloys by HIP processing at 810°C for 1 hour at 84.1MPa pressure. Wrought tungsten tubes of 15.2 and 35cm lengths, and the same diameters and wall thickness were also clad under the same conditions. Figure 12 illustrates a 316L SS clad CVD tungsten tube after finish machining of the end cap areas and ultrasonic and eddy current inspection. Figure 13 gives results of an ultrasonic inspection of this tube performed by a pulse-echo technique. Dark areas in the figure represent regions of poor sound reflection to the transducer. The dark areas on the right side and at the top and bottom of the figure represent reflection of sound away from the transducer by a surface wrinkle and indentations at each end cap juncture with the clad tungsten tube.

D. Clad Tungsten Tube Characterization and Testing

Dimensional measurements after cladding tungsten targets have not shown cladding process induced deviations from the initial straightness or roundness tolerances of the tungsten tubes. A number of targets have been thermally cycled at near plant prototypic conditions. Ultrasonic inspection techniques were used to verify the integrity of tungsten to cladding diffusion-bonded interfaces prior to, and after thermal cycling. These target assemblies, which have included one 14" long and four 6" long samples, were thermally cycled at prototypic APT conditions to more than the expected number of total component life cycles (15,000 cycles). To date, only one indication of a possible disbonded region in one target assembly (6" long, Alloy 718 clad tungsten tube) has been observed after a full thermal cycling test. This target sample is currently being further evaluated to provide additional ultrasonic inspection of the cladding/tungsten interface. All other target test samples showed no evidence of cladding disbond after thermal cycling.

V. Conclusions and Recommendations

Uniaxial bonding studies showed that excellent diffusion bonds could be produced between tungsten and Alloy 718 at 990°, 1020°, 1038° and 1065°C. A temperature of 1020°C was selected for bonding Alloy 718 to tungsten target tubes. The uniaxial bonding work also demonstrated that excellent diffusion bonds could be produced between Alloy 600 and 316L SS at 810°C. Bonds between 316L SS and tungsten made at 800°C also appeared satisfactory.

Intergranular cracking in the interior of the tungsten layer uniaxial bond samples between tungsten and Alloy 718 is associated with the high residual stresses introduced because of thermal expansion coefficient differences during cooling to room temperature from the bonding temperature.

Concerns over the stability of bonded target structures during operational thermal cycling stimulated detailed analysis and thermal cycle testing at plant prototypic conditions. The testing demonstrated that Alloy 600 and 316L clad tungsten target tubes of prototypic length, diameter and wall thickness performed as needed when subjected to 15,000 thermal cycles at plant prototypic conditions. One target tube clad with Alloy 718 demonstrated anomalous behavior and requires further study through nondestructive and destructive examination, and additional thermal cycling of this material combination.

Future work to study the effects of component dimensional tolerance variations on target assembly cooling passage clearance is required to assure the target rung configuration will have the anticipated performance. Manufacture of a significant number of targets will be required for this purpose. Possible mechanisms of cladding failure due to irradiation damage should be evaluated in irradiation tests of the target assemblies.

ACKNOWLEDGMENTS

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FIGURES

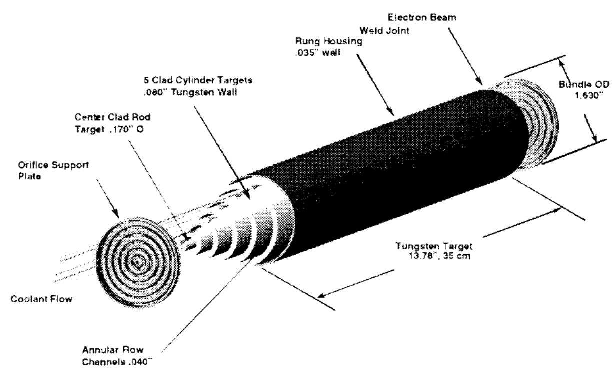


Figure 1. Target LadderRung Assembly

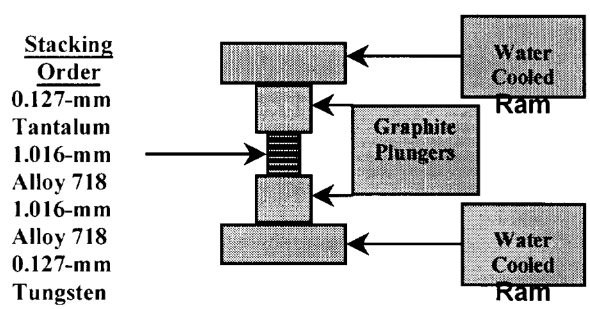


Figure 2. Hot Press Set Up Geometry for Diffusion Bonding Studies

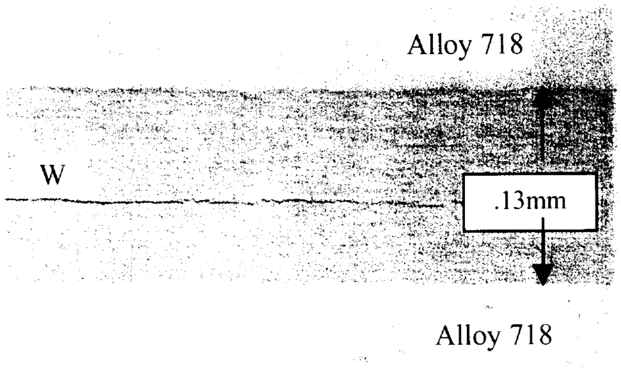


Figure 3. Microstructure of Alloy 718 Bonded to Tungsten at 1020°C for 1 Hour Note the crack at the center of the tungsten layer and excellent bond appearance.

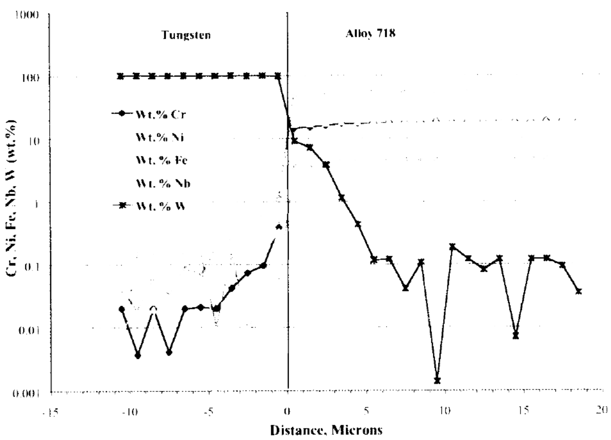


Figure 4 Concentration vs. Distance-Tungsten-to-Alloy 718 Interface Diffusion Bonded @ 1020°C for 1 Hour

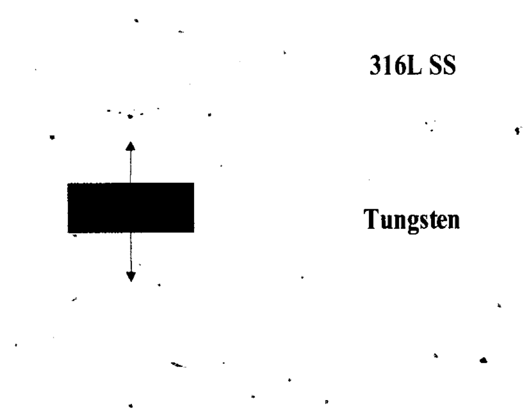
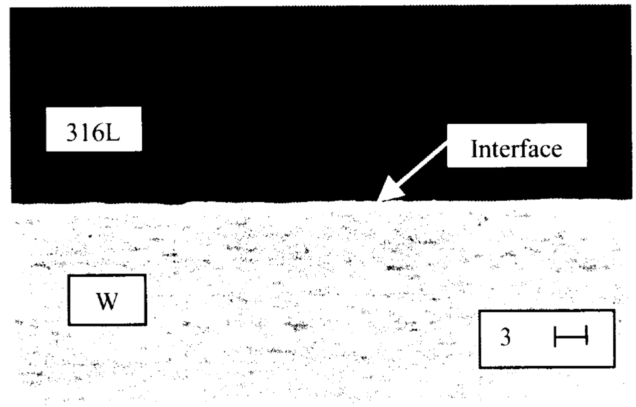
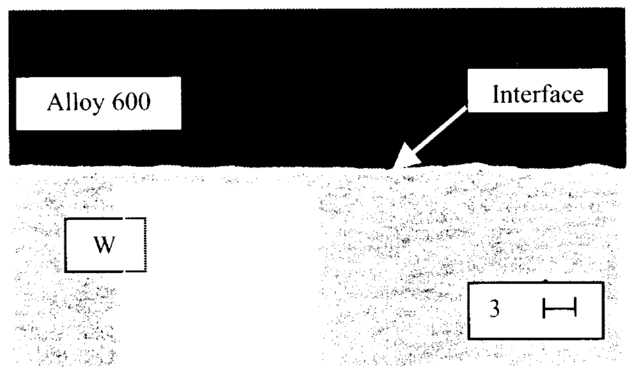


Figure 5. 316L Stainless Steel-to-Tungsten Diffusion Bond, 1 Hour @ 800°C Note uniformly bonded interface.

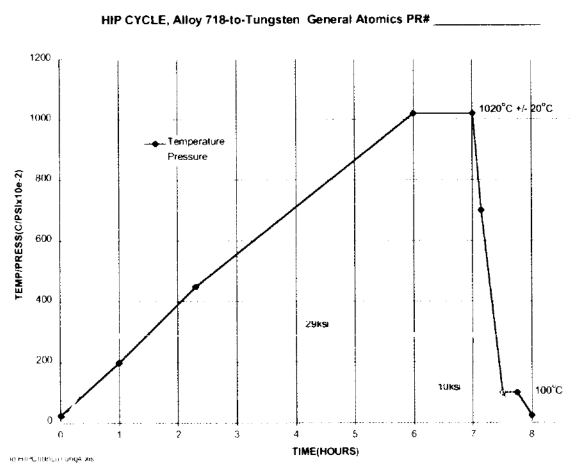


6a. 316L Stainless Steel-to-Tungsten Diffusion Bond

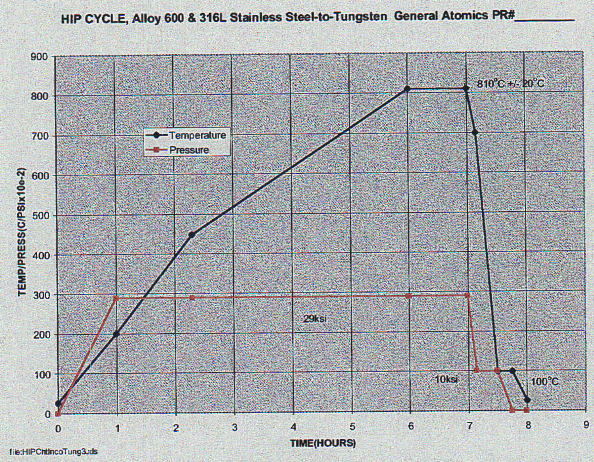


6b. Alloy 600-to-Tungsten Diffusion Bond

Figure 6. SEM Secondary Electron Detector Displays of 316L SS and Alloy 600 Bonded to Tungsten-1 Hour @ 810°C. Note bonded interfaces contain no second phases or flaws.



7a. Bond Cycle for Alloy 718 @ 1020°C



7b. Bond Cycle for Alloy 600 and 316L-to-Tungsten

Figure 7. HIP Bonding Cycles for Bonding Alloy 600, Alloy 718 & 316L SS to Tungsten Note that the pressure increases in advance of the temperature rise.

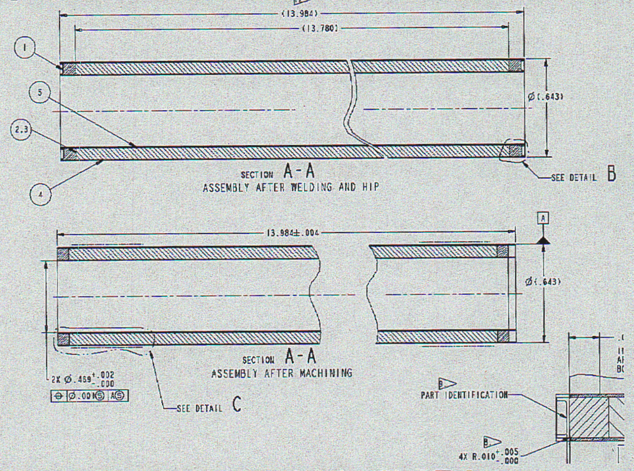


Figure 8. HIP Configuration for Clad Tubes

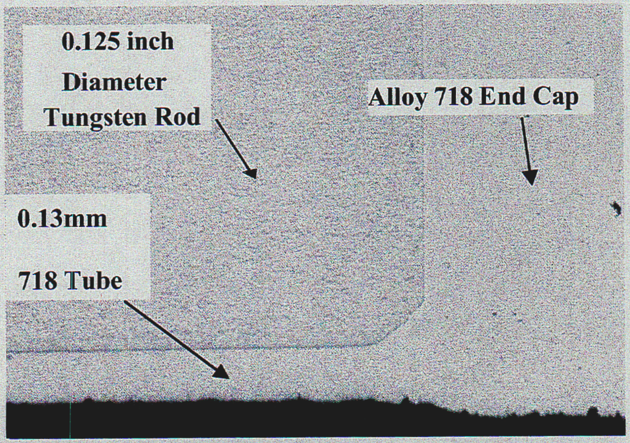


Figure 9. Powder Metallurgy Tungsten Rod Clad with Alloy 718-HIPed @ 1020°C for 1 Hour Note that the cladding has bonded to the end cap and conformed to the corner radius of the tungsten rod.

Figure 10. 51mm LongCVD Tungsten Tube Clad with Alloy 718 HIPed @ 1020°C for 1 Hour

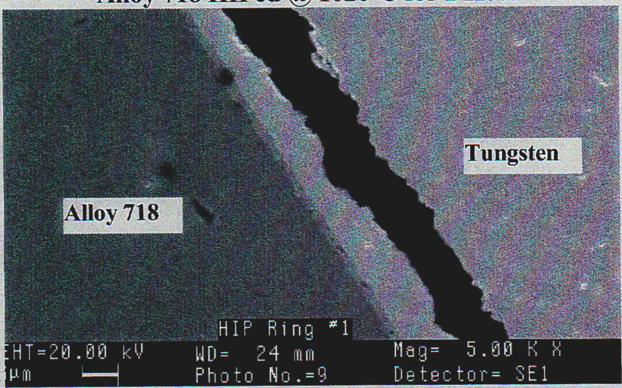
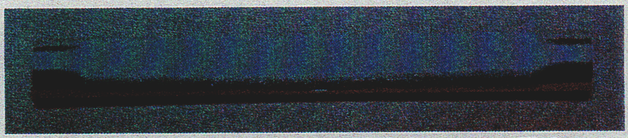
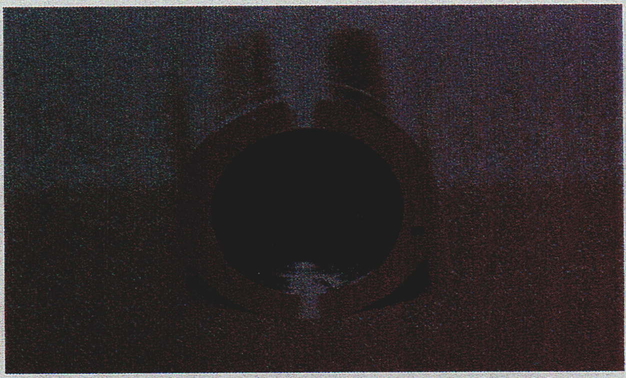


Figure 11. Alloy 718 Cladding HIP Bonded to CVD Tungsten at 1020°C for 1 Hour Note the tungsten layer adherant to the Alloy 718

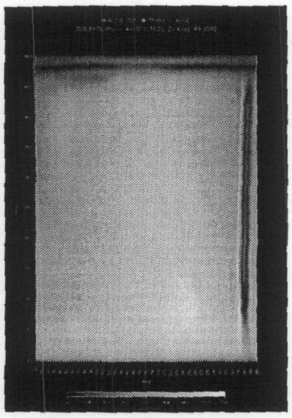


12a. Machined 316LClad CVD Tungsten Tube



12b. 316LClad CVD Tube Showing End Machining

Figure 12. 316L SS Clad CVD Tungsten Tube Note: Each end of the ⌀16.3mm, 15.4cm long assembly was machined to remove the electron beam weld bead and to bore the diameter to 11.9mm.



Technique: Pulse-Echo-Reflection from Ultrasound Focussed on Near ID Surface

Results:

Excellent Bonding of Cladding to OD and ID of Tungsten Ring Surface Fold and Depressions at Ends of Tube Reflect Sound Away from Transducer

Note: Planar Display of Sound Transmission Along Tube Circumference

Figure 13. Display of Ultrasonic Examination Results for a CVD Tungsten Tube Clad with 316L Stainless Steel